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DIRECT CAST TITANIUM ALLOY STRIP

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This research project successfully demonstrated the feasibility of induction melting titanium alloys in a segmented copper crucible and casting them into solid strip up to 300 mm (12 in) wide from a unique graphite tundish using melt overflow rapid solidification technology (MORST). A U.S. Patent Application was filed on the invention. Ti-6Al-4V, Ti-14Al-21Nb and Ti-34Al-4V alloys were cast into 300-mm (12-in)-wide strip. The system casts strip that has low levels of oxygen, hydrogen, nitrogen and carbon. There was no evidence of carbon contamination from the graphite tundish. The objective of casting 0.125-mm (0.005-in)-thick strip was also realized in casting strip up to 32 mm (1.5 in) wide.

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EXECUTIVE SUMMARY

This research project successfully demonstrated the feasibility of induction melting titanium alloys in a segmented copper crucible and casting them into solid strip up to 300 mm (12 in) wide from a unique graphite tundish using melt overflow rapid solidification technology (MORST). A U.S. Patent application was filed on the invention. Ti-6Al-4V, Ti-14Al-21Nb and Ti-34Al-4V alloys were cast into 300-mm (12-in)-wide strip. The system casts strip that has low levels of oxygen, hydrogen, nitrogen and carbon. There was no evidence of carbon contamination from the graphite tundish. The objective of casting 0.125-mm (0.005-in)-thick strip was also realized in casting strip up to 32 mm (1.5 in) wide.

The process parameters have the greatest influence on the thickness of the cast strip were the casting speed, the depth of liquid in contact with the substrate, and the physical properties of the liquid (viscosity and surface tension). The melt overflow system used for these experiments did not achieve steady-state casting conditions. In fact, the casting conditions were continually changing.

It appears that the wetting characteristics of liquid titanium alloys on metallic substrates were greatly affected by the substrate material and temperature. The substrate material used for casting Ti-6Al-4V alloy and Ti-14Al-21Nb alloy strip was molybdenum. Both molybdenum and Ti-6242 alloy substrates were used to cast gamma titanium alloys. All of the 350-mm (14-in) wide chill rolls had a diamond-shaped knurl pattern on the circumference.

The microstructure of the as-cast Ti-6Al-4V alloy exhibited colonies of single-phase martensitic alpha-prime laths. Thicker cast strip resulted in coarser laths. The microstructures of the Ti-14Al-21Nb samples were dominated by Widmanstatten (acicular) alpha two. There were small pockets of retained beta in the samples which indicated a fairly slow cooling rate in the solid state. The microstructures of as-cast gamma aluminide strip contained regions of equiaxed gamma and colonies of thick lamellar gamma with thin, inter-lamellar alpha-2. The microstructure of the 1-mm (0.039-in)-thick gamma strip was dominated by the lamellar gamma with inter-lamellar alpha-2 while the microstructure of 0.4-mm (0.016-in)-thick gamma strip was dominated by equiaxed gamma.

Collection and handling of the as-cast strip will be essential for recovering any useful lengths of material. It is likely that grinding of the as-cast strip, followed by rolling, is feasible to produce the uniform strip dimensions and optimum physical properties.

INTRODUCTION

This contract was awarded to Ribbon Technology Corporation (Ribtec) under Phase II of the DoD Small Business Innovation Research (SBIR) Program. The Phase I SBIR research program, entitled "Direct Cast Titanium Aluminide Strip," (Air Force Contract Number F33615-86-C-5139) successfully demonstrated the feasibility of casting rapidly solidified titanium alloy strip by the melt overflow process using induction melting of titanium alloys in a segmented copper crucible. The Phase II project focused scaling-up the process to cast titanium aluminide strip up to 300 mm (12 in) wide.

Ribtec's melt overflow process involves the transfer of liquid metals and alloys from a molten reservoir onto the surface of a rotating chill roll (Figure 1). Unlike conventional melt spinning techniques, the melt is not extruded through an orifice; rather, the molten material flows over a solid surface from a molten reservoir until it comes in contact with a moving chill surface. Rapidly solidified foils, fibers, flakes, filaments, strips, and particles are among the products that can be cast directly by melt overflow. In general, the final product form depends on the geometry of the casting surface [1-3].

Skull melting techniques are required for melting titanium and other reactive metals. Induction melting of titanium can be performed in a segmented, water-cooled copper crucible shown schematically in Figure 2 [4,5]. In 1980, the Duriron Company decided to investigate production of titanium and zirconium castings using the "induction-slag" process developed by the U.S. Bureau of Mines (USBM) [6,7]. The original USBM process used a calcium floride slag to electrically insulate the titanium melt from the crucible wall. Duriron discovered that the calcium floride could be eliminated without damaging the crucible [8]. Duriron calls the flux-free process "induction skull" melting.

The combination of induction melting of titanium in a segmented crucible with melt overflow rapid solidification technology results in a process capable of direct casting titanium alloy sheet and strip to near-net-shape. A melt overflow casting machine was designed and built for casting titanium alloy strip inside the induction skull furnace operated by the Duriron Company.

Many advanced Air Force technology system designs including propulsion (IHPTET) and structures (NASP) rely heavily on the successful development of titanium metal matrix composites based on the Ti_3Al and TiAl matrices. Matrix foil material of either base composition is very costly and difficult or impossible to obtain commercially. Direct casting of titanium alloy sheet to near-net-shape affords the potential for obtaining foils of matrix materials at potentially lower costs and shorter lead

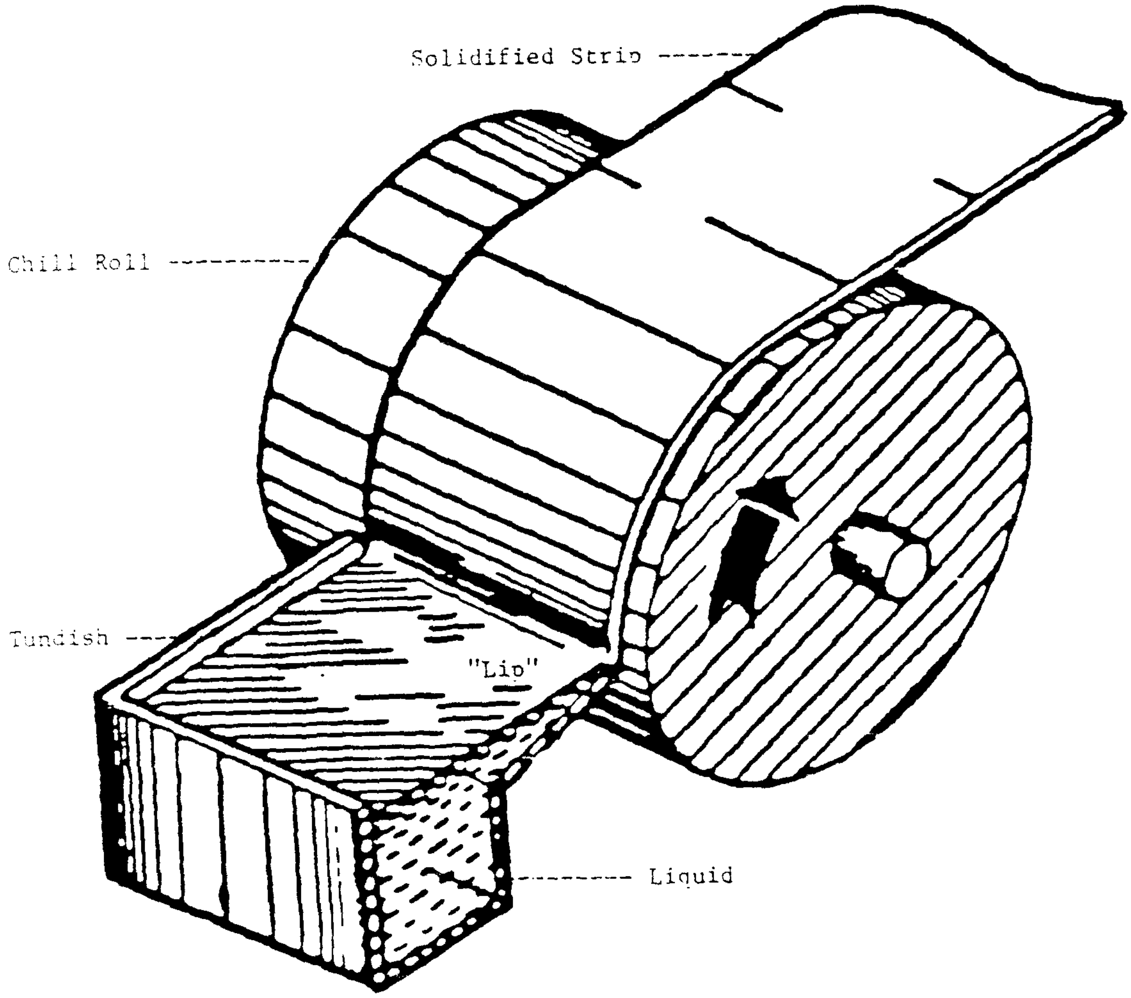


Figure 1: Schematic of the Melt Overflow Process

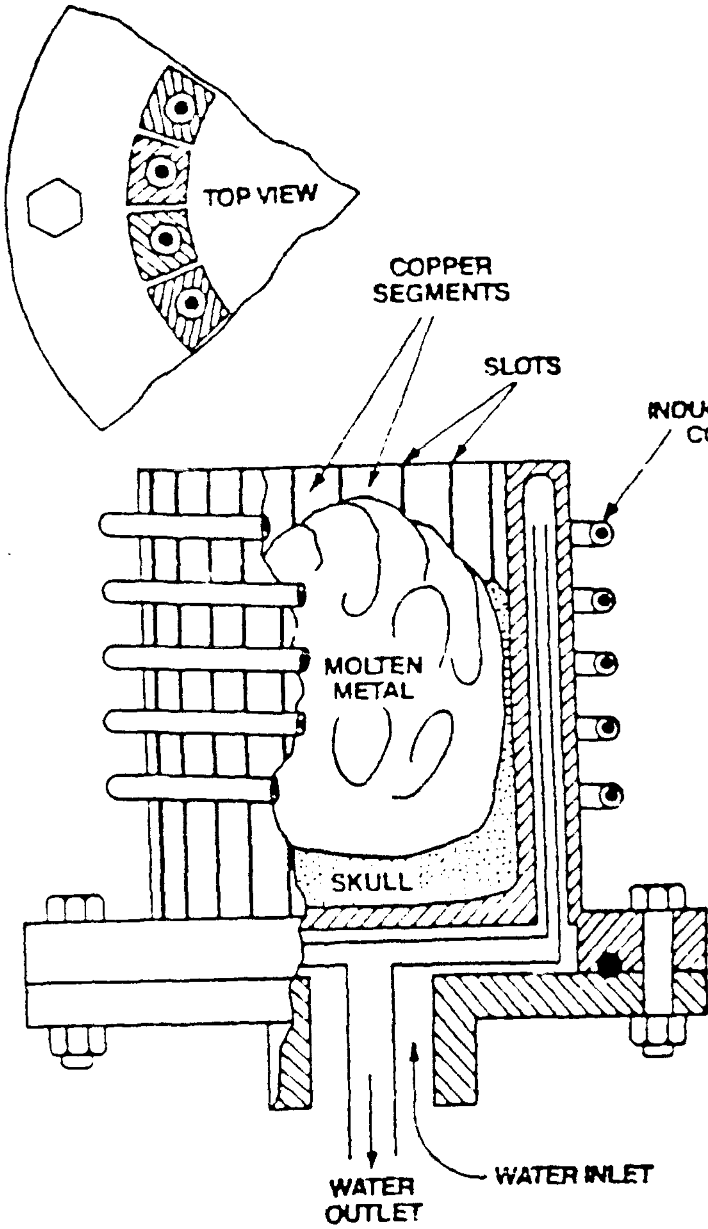


Figure 2: Schematic of Segmented Copper Crucible
in the Induction Skull Furnace

times. The melt overflow process offers the following advantages of rapid solidification: unique alloy compositions, potentially enhanced mechanical properties, reduced effects of texture present in conventionally rolled material, and at potentially lower cost than ingot metallurgy techniques.

The Phase II research project was organized into five different tasks, as follows:

Task I - Identify Substrate Materials
Task II - Process Design
Task III - Physical Modeling
Task IV - Processing Experiments
Task V - Process Evaluation

The work performed under each task will be reported separately in the Procedures and Results sections of this report.

The first task was to identify substrate materials for casting the alpha-2 and gamma titanium aluminides. During the Phase I research project, we found that titanium aluminides did not wet copper or brass chill roll substrates. It was essential to the success of this project to find a substrate material for casting Ti-aluminides. All of the Task I substrate experiments were performed at Ribtec in a laboratory-scale plasma melt overflow casting furnace.

The second task was to design a melt overflow strip casting machine for use with induction melting. The melting was to be performed in an induction skull furnace operated by the Duriron Company in Dayton, Ohio. The design of the casting process included the design of a funnel and tundish system for distributing the liquid titanium on the chill roll.

The third task was to physically model the casting process using water and liquid aluminum in place of titanium. The fluid flow in the tundish and funnel prototypes were modeled,and the designs were refined during this task.

The fourth task was the actual casting experiments. Three alloys were specified by the Air Force to be cast into 300-mm (12-in)-wide strip: Ti-6Al-4V alloy, Ti-14Al-21Nb alloy and Ti-34Al-4V alloy. These experiments were performed at the Duriron Company in Dayton, Ohio.

The fifth task was to evaluate the melt overflow process for casting Ti-aluminide strip. Titanium alloy strip cast during Tasks I and IV were evaluated using chemical analyses, transmission electron microscopy (TEM) and wavelength dispersive spectroscopy (WDS).

PHASE II TECHNICAL OBJECTIVES

The primary objective of the Phase II research project was to demonstrate the feasibility of casting rapidly solidified titanium aluminide strip, 300-mm (12-in)-wide using Ribtec's Melt Overflow Process. The widest titanium alloy strip cast during the Phase I research project was 178 mm (7 in).

A second objective of this study was to produce strip less than 0.125 mm (0.005 in) thick to obtain higher cooling rates. In general, the strip cast during the Phase I research project was 0.25 mm (0.010) thick or greater.

A final goal of the project was to develop a better understanding of the effects of melt overflow process variables on strip dimensions, uniformity and cooling rates.

PROCEDURES

Task I - Identify Substrate Materials. The purpose of this task was to select the best chill roll substrate materials for casting wide titanium alloy sheet. Copper and yellow brass substrates were used during Phase I experiments with limited success: Ti-aluminides did not uniformly wet the copper or brass subscrates to cast full width strip.

A laboratory benchtop-scale plasma melt overflow machine operated by Ribtec was used to conduct experiments to identify the best substrate materials for casting titanium alloys. The unit was used for casting 100 g quantities of refractory metals and was modified to cast titanium. The controls were upgraded to monitor the process parameters during each experiment.

Initially, five different substrate materials were selected for experiments with Ti-6Al-4V alloy and Ti-aluminide alloys: copper, yellow brass, molybdenum, Grade H-13 steel and plasma sprayed molybdenum on copper. Seven additional substrates were used for experiments with Ti-aluminides: pure aluminum, pure chromium and titanium alloy Ti-6Al-2Sn-4Zr-2Mc (Ti-6242), electroplated silver on copper, electroplated chromium on copper, electroplated chromium on steel and copper oxide.

The chill roll dimensions were 190 mm (7.5 in) diameter by 50 mm (2 in) wide. The chill rolls were turned on a lathe then the surface textures were turned on the chill rolls' circumference. The two textured surfaces were a 14-pitch diamond knurl and 100-thread-per-inch helical grooves. On composite rolls, substrate textures were applied to the chill roll surfaces before coating. Silver was electro-plated on a copper chill roll that was threaded on the circumference. Chromium was electroplated on a C110 copper and Grade H-13 steel chill rolls that had a 14-pitch diamond knurl on the circumference. The copper oxide surface was achieved by baking a threaded copper chill roll in air at 150°C (300°F) for 1 hour. A tenacious black oxide formed on the chill roll.

A standardized plasma melt overflow furnace test procedure was used for each experiment. The alloys were melted in a water cooled copper hearth using an argon plasma with a current of 400 amperes and 44 volts at 64-mm (2.5-in) standoff. The Ti-34Al-4V alloy was alloyed from a 50Al-50V master alloy, pure aluminum shot and sponge titanium. The Ti-6Al-4V alloy and Ti-14Al-21Nb alloy were prealloyed.

Task II - Process Design. A melt overflow casting machine was designed and built at Ribtec for operation inside the induction skull casting furnace at Duriron Company. The drawings were made using AutoCAD computer aided design software installed on a personal computer and plotted with a digital plotter.

Task III - Physical Modeling. Fluid flow in the funnel and tundish were modeled by liquid aluminum in an alumina or steel tundish and by water flowing in an acrylic tundish.

Alumina tundishes were made using a 95% alumina castable refractory poured into wooden molds. The green parts were dried overnight at 65°C (150°F) then fired at 1100°C (2000°F) for six hours in an electrical resistance furnace then furnace cooled.

The steel tundish was made by shearing steel plate then welding the plates together using GMAW. The acrylic tundishes were made by cutting 1/4-inch-thick acrylic sheet then assembled using acrylic solvent cement.

Task IV - Processing Experiments. Before each experiment, the chill roll caster components were assembled. The components included a graphite funnel, a graphite tundish, a solid molybdenum or solid titanium chill roll, a 2-hp DC motor and a tachometer. The motor was mounted under the chill roll and the tachometer was mounted beside it. The assembled unit was installed in the lower chamber of the Duriron induction skull furnace. The base of the caster frame was clamped to the platen in the furnace.

Figure 3 shows a schematic of the chill roll caster assembly mounted in the lower chamber of the Duriron furnace. The chill roll assembly was raised on the platen into the upper melting chamber of the furnace. The lower chamber door was closed and sealed. The electrical and signal connections were made through the upper chamber. The induction slag furnace was charged with approximately 14 kg (30 lb) of melting stock for each experiment. Alloying additions were placed on a vibratory feeder. No flux or slag was used during any of the experiments. After charging, the upper chamber door was closed and sealed.

The induction slag furnace was evacuated to a pressure of approximately 10 microns. The vessel was then filled to roughly one half atmosphere of argon. The power was turned on and gradually increased in stages as the melting progressed. After the charge was fully melted, alloy additions (if any) were made with the vibratory feeder. As soon as the melt temperature stabilized, the chill roll was brought to the proper rotational speed.

The casting sequence is shown in Figures 4 through 7. The Duriron induction slag furnace has an automatic, programmable pour rate. The furnace power was shut off and the crucible was tilted automatically to pour the liquid titanium alloys. The liquid was poured directly into the graphite funnel (Figure 4). The graphite tundish had two 25-mm (1-in)-diameter nozzles at the bottom to meter the liquid into the graphite tundish. Once the tundish was filled, 300-mm (12-in) wide titanium strip was cast

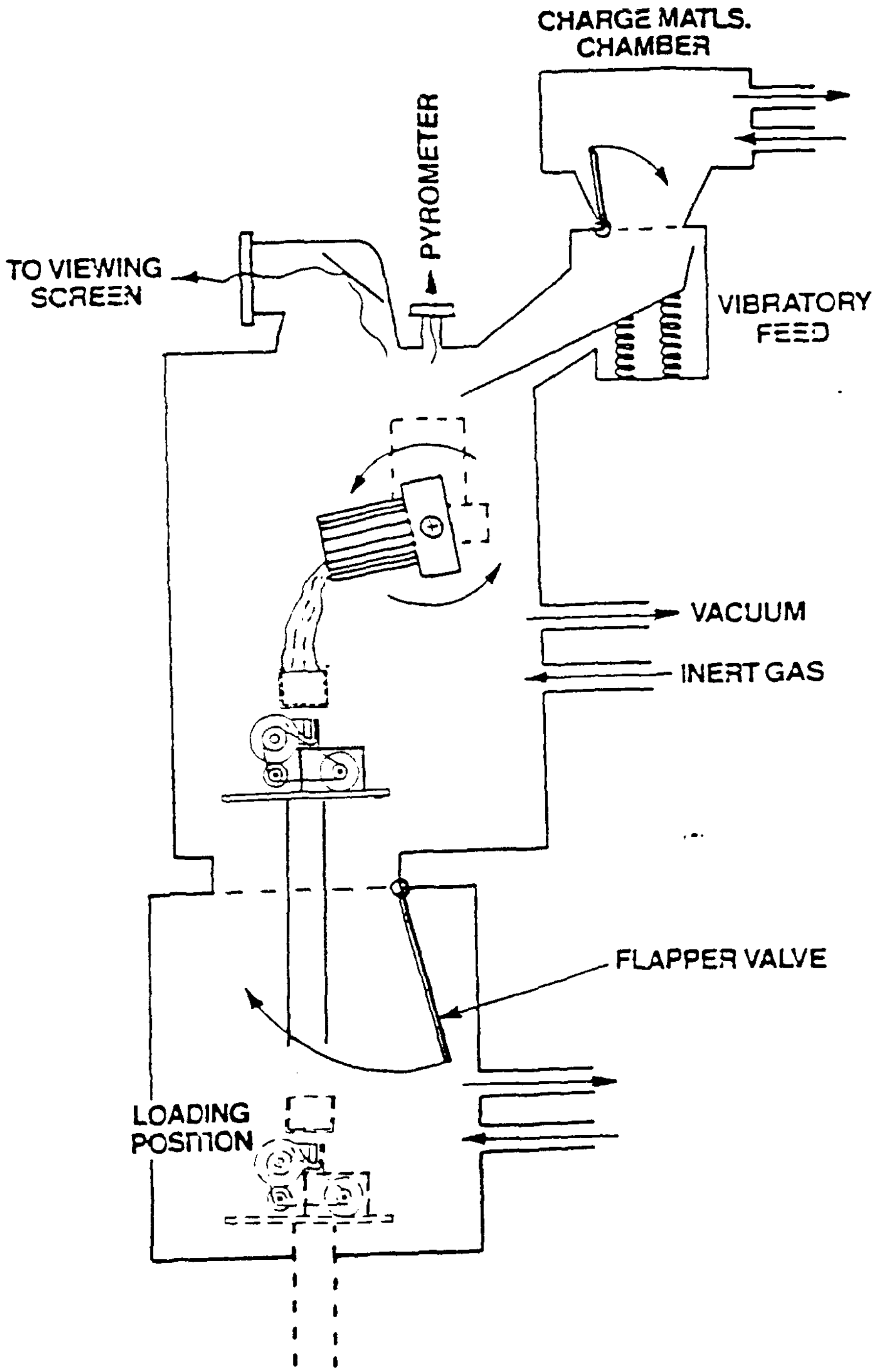


Figure 3. Schematic of Melt Overflow Casting Machine in the Induction Skull Furnace

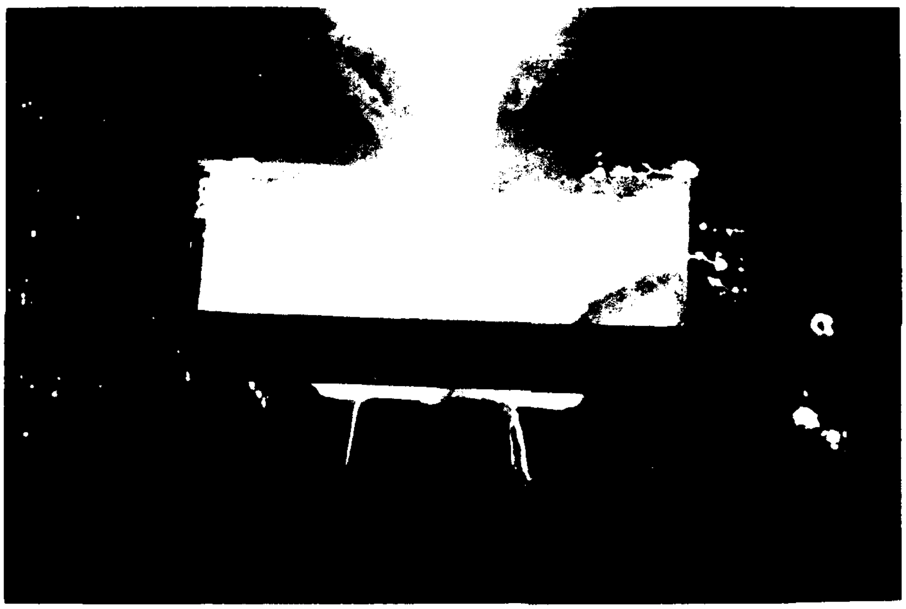


Figure 4. Photograph of Pouring Titanium from the Induction Skull Furnace

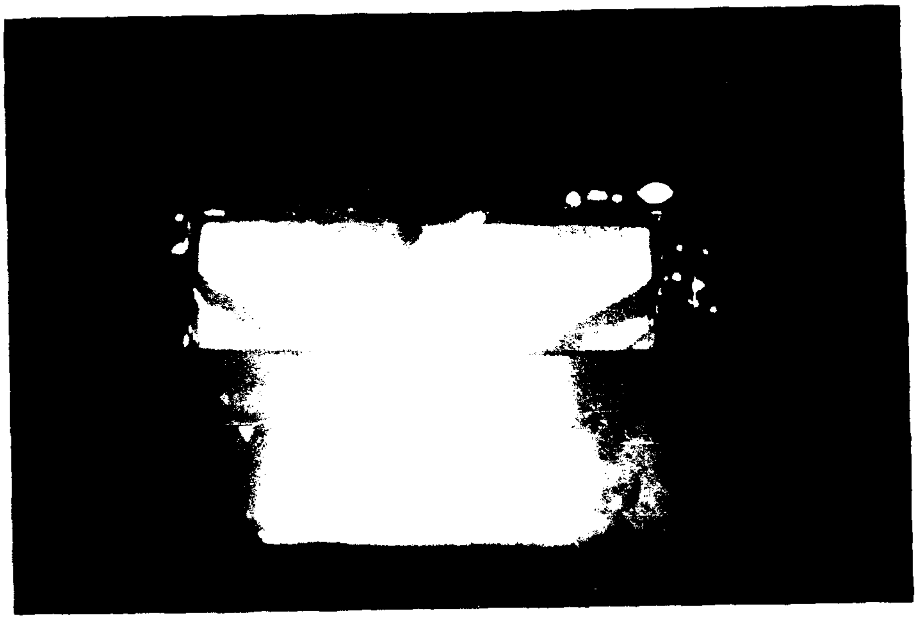


Figure 5. Photograph of Casting 300 mm Wide Titanium Strip

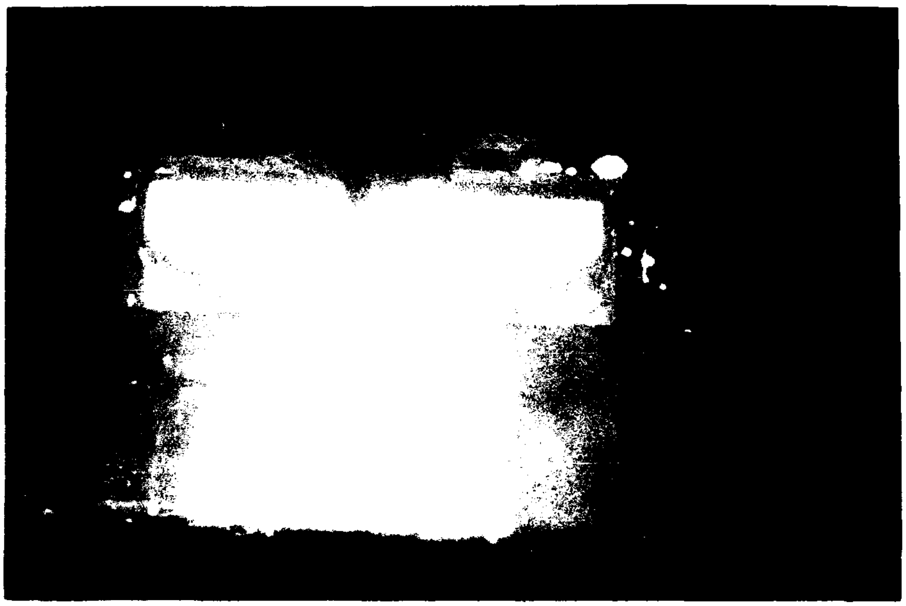


Figure 6. Photograph of the End of a Casting

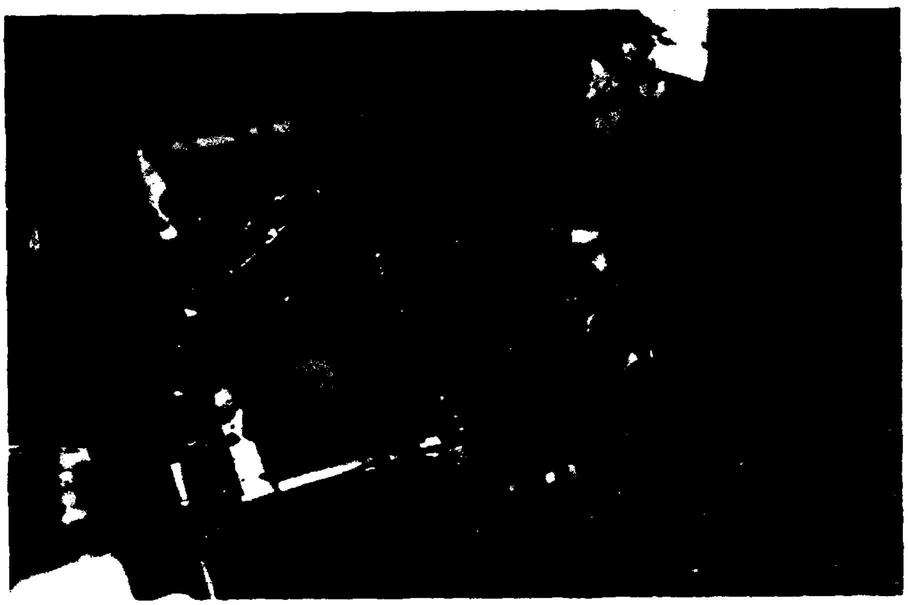


Figure 7. Photograph of Melt Overflow Casting Machine in the Induction Skull Furnace

(Figure 5). As the liquid in the tundish froze, narrower strip was cast (Figure 6). The entire casting took place in a few seconds.

The furnace was allowed to cool for up to 1 hour before it was evacuated, filled with air and opened. Figure 7 shows the casting machine immediately after an experiment. The photograph was taken from the upper chamber of the Duriron furnace. It shows the close proximity between the chill roll and the inside wall of the Duriron furnace. The titanium strip usually piled up between the chill roll and the furnace wall. After opening the chamber, the titanium strip was removed. The chill roll assembly was removed in the reverse steps of the installation procedure described above.

Task V - Process Evaluation. The process evaluation consisted of chemical analyses, transmission electron microscopy (TEM) and wavelength dispersive spectroscopy (WDS).

The carbon analysis was performed with a LECO IR-12, the nitrogen and oxygen analysis was performed with a LECO TC-436 and the hydrogen analysis was performed with a LECO RH-1. All of the chemical analyses were performed at the Duriron Company.

Portions were removed from the ribbons and ground to a thickness of approximately 200 μm. Discs, 3 mm (0.12 in) in diameter, were cut from the slices by trepanning using an abrasive slurry drill. The discs were thoroughly degreased and cleaned using ultrasonic baths of aqueous and organic solvents. Thin foils were prepared from the discs using the twin-jet electropolishing technique in a Struers Tenupol 3 using an electrolyte of 5 vol% sulphuric acid in methanol. Acceptable specimens were obtained at thinning currents of 50 mA to 150 mA and electrolyte temperatures of -30°C to -50°C. The thin foils were examined in the two transmission electron microscopes (TEM) within the Central Electron Optics Facility at the Ohio State University: a JEOL 200CX operating at 200 kV and a Philips CM12 operating at 120 kV.

RESULTS

Task I - Identify Substrate Materials. We conducted a series of controlled experiments to evaluate five different substrate materials: copper, yellow brass, molybdenum, Grade H-13 steel, and copper coated with molybdenum. Each substrate material was tested with two surface textures on the chill rolls' circumference: a 14-pitch diamond knurl and helical machine threads (100 per inch). Each substrate was tested at casting speeds of 3 m/s (10 ft/s) and 5 m/s (16 ft/s). After these initial 20 experiments were performed for each alloy, the two most promising substrates were tested at casting speeds of 7 m/s (23 ft/s) and 10 m/s (33 ft/s).

The results of the experiments to cast Ti-6Al-4V alloy are presented in Table 1. The experiments demonstrated that a solid molybdenum substrate with a knurled surface cast the best quality ribbons. By contrast, the molybdenum coated copper casting surface was the worst substrate tested. The as-deposited plasma spray coating was rough and porous causing the liquid titanium to stick to the surface. Machining thread-like grooves on the surface did eliminate the sticking of the ribbon to the substrate, but produced relatively thick strip. Porosity was evident after visual inspection of the machined surface.

Copper substrates were almost as good as molybdenum substrates in casting the Ti-6Al-4V alloy. Ribbons cast on both copper and molybdenum substrates at 7 m/s and 10 m/s were "feathery" with jagged edges and voids. The best cast surface quality was attained at casting speeds of 2 m/s. Based on our experiments, it appears that the best Ti-6Al-4V alloy ribbons were cast on pure molybdenum chill rolls with a knurled circumference at a casting rate of 2 m/s.

Two titanium aluminide compositions were investigated: Ti-14Al-21Nb (alpha-2 aluminide) and Ti-34Al-4V (gamma aluminide). The results of the substrate screening experiments for Ti-aluminides are presented in Tables 2 and 3. The data in Tables 2 and 3 show that the objective of casting 0.125 mm (0.005 in) thick titanium aluminide strip can be realized. This objective was accomplished during experiments 2.4, 2.7, 2.10, 2.14, 2.21, 3.8 and 3.21.

The width of the Ti-aluminide strip cast during these experiments may be a better measure of the substrate wetting characteristics than the thickness of the strip. Ribbons were cast from a 32-mm (1.25-in)-wide slot machined on one side of the copper hearth. None of the experiments reported in Tables 2 or 3 resulted in 32-mm (1.25-in)-wide strip.

From Table 2, it appears that a knurled molybdenum substrate also provides the best surface for casting the Ti-14Al-

TABLE 1. RESULTS OF EXPERIMENTS TO CAST Ti-6Al-4V ALLOY RIBBONS

EXPERIMENT	CASTING SPEED (m/s)	SUBSTRATE MATERIAL	SUBSTRATE TEXTURE	RIBBON THICKNESS* (mm)	RIBBON THICKNESS* (in)	RIBBON WIDTH* (mm)	RIBBON WIDTH* (in)
1.1	3	Cu	KNURL	0.23	0.009	11.7	0.46
1.2	5	Cu	KNURL	0.23	0.009	10.4	0.41
1.3	3	Cu	GROOVED	0.20	0.008	9.4	0.37
1.4	5	Cu	GROOVED	0.20	0.008	10.9	0.43
1.5	3	BRASS	KNURL	0.20	0.008	5.1	0.20
1.6	5	BRASS	KNURL	0.20	0.008	7.6	0.30
1.7	3	BRASS	GROOVED	0.20	0.008	9.4	0.37
1.8	5	BRASS	GROOVED	0.20	0.008	7.9	0.31
1.9	3	Mo	KNURL	0.20	0.008	12.7	0.50
1.10	5	Mo	KNURL	0.18	0.007	6.4	0.25
1.11	3	Mo	GROOVED	0.20	0.008	7.6	0.30
1.12	5	Mo	GROOVED	0.23	0.009	10.9	0.43
1.13	3	Mo/Cu	AS-SPRAYED	1.27	0.050	12.7	0.50
1.14	5	Mo/Cu	AS-SPRAYED	1.42	0.056	11.7	0.46
1.15	3	Mo/Cu	GROOVED	0.25	0.010	8.6	0.34
1.16	5	Mo/Cu	GROOVED	0.20	0.008	7.1	0.28
1.17	3	STEEL	KNURL	0.15	0.006	6.4	0.25
1.18	5	STEEL	KNURL	0.15	0.006	6.4	0.25
1.19	3	STEEL	GROOVED	0.23	0.009	7.4	0.29
1.20	5	STEEL	GROOVED	0.18	0.007	6.1	0.24
1.21	7	Cu	KNURL	0.15	0.006	8.9	0.35
1.22	7	Mo	KNURL	0.15	0.006	10.2	0.40
1.23	10	Mo	KNURL	0.13	0.005	10.2	0.40
1.24	10	Cu	KNURL	0.15	0.006	10.2	0.40
1.25	2	Mo	KNURL	0.18	0.007	15.2	0.60

* Strip thicknesses and widths vary. Dimensions given are averaged over ten measurements.

TABLE 2. RESULTS OF EXPERIMENTS TO CAST Ti-14Al-21Nb ALLOY RIBBONS

EXPERIMENT NUMBER	CASTING SPEED (m/s)	SUBSTRATE MATERIAL	SUBSTRATE TEXTURE	RIBBON THICKNESS* (mm)	RIBBON THICKNESS* (in)	RIBBON WIDTH* (mm)	RIBBON WIDTH* (in)
2.1	3	Cu	KNURL	0.20	0.008	13.6	0.536
2.2	5	Cu	KNURL	0.20	0.008	8.9	0.349
2.3	3	Cu	GROOVED	0.23	0.009	13.5	0.533
2.4	5	Cu	GROOVED	0.09	0.003	10.7	0.422
2.5	3	BRASS	KNURL	0.16	0.006	13.0	0.513
2.6	5	BRASS	KNURL	0.15	0.006	13.9	0.547
2.7	3	BRASS	GROOVED	0.11	0.004	13.1	0.516
2.8	5	BRASS	GROOVED	0.14	0.006	11.8	0.465
2.9	3	Mo	KNURL	0.21	0.008	15.5	0.612
2.10	5	Mo	KNURL	0.12	0.005	20.4	0.803
2.11	3	Mo	GROOVED	0.18	0.007	11.1	0.435
2.12	5	Mo	GROOVED	0.18	0.007	12.2	0.480
2.13	3	Mo/Cu	KNURL	0.26	0.010	13.3	0.525
2.14	5	Mo/Cu	KNURL	0.12	0.005	9.3	0.365
2.15	3	Mo/Cu	GROOVED	0.17	0.007	11.1	0.435
2.16	5	Mo/Cu	GROOVED	0.18	0.007	12.2	0.480
2.17	3	STEEL	KNURL	0.17	0.007	13.4	0.529
2.18	5	STEEL	KNURL	0.23	0.009	13.9	0.549
2.19	3	STEEL	GROOVED	0.15	0.006	13.4	0.528
2.20	5	STEEL	GROOVED	0.18	0.007	13.4	0.528
2.21	7	Mo	GROOVED	0.10	0.004	13.5	0.530
2.22	7	Mo/Cu	KNURL	0.17	0.007	9.4	0.371
2.23	7	STEEL	KNURL	0.17	0.006	8.5	0.335
2.24	10	Mo	GROOVED	0.16	0.006	13.9	0.548
2.25	10	Mo/Cu	KNURL	0.23	0.009	23.4	0.921
2.26	10	Mo/Cu	KNURL	0.17	0.007	12.4	0.487
2.27	10	STEEL	KNURL	0.19	0.007	7.7	0.302

* Strip thicknesses and widths vary. Dimensions given are averaged over ten measurements.

TABLE 3. RESULTS OF EXPERIMENTS TO CAST Ti-34Al-4V ALLOY RIBBONS

EXPERIMENT NUMBER	CASTING SPEED (m/s)	SUBSTRATE MATERIAL	SUBSTRATE TEXTURE	RIBBON THICKNESS* (mm)	RIBBON THICKNESS* (in)	RIBBON WIDTH* (mm)	RIBBON WIDTH* (in)
3.1	3	Cu	KNURL	NA	NA	NA	NA
3.2	5	Cu	KNURL	0.23	0.009	10.4	0.409
3.3	3	Cu	GROOVED	NA	NA	NA	NA
3.4	5	Cu	GROOVED	NA	NA	NA	NA
3.5	3	BRASS	KNURL	0.20	0.008	3.2	0.126
3.6	5	BRASS	KNURL	0.16	0.006	6.1	0.240
3.7	3	BRASS	GROOVED	0.30	0.012	14.1	0.555
3.8	5	BRASS	GROOVED	0.13	0.005	9.8	0.386
3.9	3	Mo	KNURL	0.21	0.008	12.1	0.476
3.10	5	Mo	KNURL	0.16	0.006	13.3	0.524
3.11	3	Mo	GROOVED	0.28	0.011	9.7	0.382
3.12	5	Mo	GROOVED	0.12	0.005	13.8	0.543
3.13	3	Mo/Cu	KNURL	0.38	0.015	7.9	0.311
3.14	5	Mo/Cu	KNURL	0.19	0.007	16.3	0.641
3.15	3	Mo/Cu	GROOVED	0.40	0.016	4.6	0.181
3.16	5	Mo/Cu	GROOVED	0.16	0.006	12.5	0.492
3.17	3	STEEL	KNURL	0.30	0.012	7.9	0.311
3.18	5	STEEL	KNURL	0.31	0.012	16.1	0.634
3.19	3	STEEL	GROOVED	0.16	0.006	9.6	0.378
3.20	5	STEEL	GROOVED	0.18	0.007	13.9	0.547
3.21	7	Mo	KNURL	0.12	0.005	16.6	0.652
3.22	7	STEEL	KNURL	0.29	0.011	3.3	0.130
3.23	10	Mo	KNURL	0.14	0.006	8.7	0.262
3.24	10	STEEL	KNURL	0.27	0.011	5.9	0.233

* Strip thicknesses and widths vary. Dimensions given are averaged over ten measurements.

21Nb alloy. Alpha-2 ribbons with the best surface quality were cast on a Grade H-13 steel roll with a knurled circumference.

The results for the Ti-34Al-4V alloy were less conclusive. From Table 3, a knurled molybdenum substrate was selected as the best substrate material, but it cast a shard rather than a continuous ribbon. The Ti-34Al-4V alloy appeared to form a high surface tension skin on the surface of the liquid pool during plasma melting that inhibited casting.

Four additional coating materials were evaluated during experiments to cast gamma aluminides: copper oxide, silver-plated copper, chrome-plated copper and chrome-plated steel. The copper oxide on a threaded copper roll did not improve the wetting of the Ti-3Al-4V alloy at casting speeds of 2 m/s to 10 m/s. The gamma aluminide did not wet the silver-plated threaded copper substrate. The chrome-plated steel substrate worked better than the chrome-plated copper substrate. Both had a 14-pitch knurl on the circumference before plating. The wetting of the chrome-plated chill rolls showed a significant improvement during the initial experiment but lost effectiveness during subsequent experiments as the coating wore off.

Three additional chill rolls were machined from pure aluminum, pure chromium and Ti-6Al-2Sn-4Zr-2Mo (Ti-6242) alloy. All of these chill rolls had a 14-pitch diamond knurl machined on their circumference. The gamma aluminide did not wet the surface of the aluminum chill roll. Experiments were performed to cast Ti-34Al-4V alloy ribbons at speeds ranging from 1 m/s (3 ft/s) to 2 m/s (7 ft/s) on the Ti and Cr chill rolls.

Several experiments were performed with the molybdenum, chromium, steel, and Ti-6242 chill rolls without water cooling to simulate the processing experiments of Task IV. The chromium, molybdenum and titanium alloy chill rolls cast full width Ti-34Al-4V alloy ribbons without the ribbon sticking to the chill roll. Therefore, either molybdenum, chromium or Ti-6242 alloy knurled substrates can be used to cast gamma titanium alloys.

Task II - Process Design. A new casting machine was designed for the Processing Experiments in Task IV. The process design reflected the limitations imposed by use of the Duriron facility. First, all of the electrical connections had to be made through a single flange on the upper chamber. The only utilities available were 120 VAC electric: no water cooling of the caster was possible. Finally, the entire casting machine had to pass through a 0.7-m (30-in)-diameter cylindrical passage between the molding chamber and casting chamber of the induction skull furnace at Duriron.

One of the problems associated with the casting experiments conducted during the Phase I research project was the rapid

freezing of the liquid titanium in the pour tube, funnel and tundish. First, the pour tube was eliminated from the new design. Next, the wall thicknesses of all graphite parts were reduced to 6 mm (1/4 in) for the tundishes and funnels. Finally, the design of the tundish and funnel were modified during the modeling experiments of Task III.

Figure 8 shows a schematic of the final tundish design. The liquid titanium was poured from two holes in the funnel to opposite sides of the tundish, then flow together onto the chill roll. This design permitted maximum flow through the funnel and tundish before the liquid titanium solidifies. A United States Patent Application was filed for this unique tundish system.

Figures 9 through 11 present three projections from an assembly drawing that shows the melt overflow casting machine installed inside a schematic outline of Duriron's induction skull furnace. The top view (Figure 9) shows the caster inscribed in a 0.7-m (28-in)-diameter circle. The funnel was centered in the circle to be in the correct position for pouring the liquid titanium from the induction skull crucible. The front view (Figure 10) shows that the caster cannot be fully raised into the melting chamber. The side view (Figure 11) shows the position of the funnel, tundish and chill roll relative to the induction furnace.

Task III - Physical Modeling. The original funnel and tundish design called for the liquid titanium to stream from a single orifice to the tundish. This single orifice system creates large velocity gradients in the fluid flowing in the tundish. We recognized that the uniformity of the fluid flow in the tundish could be improved by using a double orifice funnel system.

Full-scale plexiglas models of the funnel and tundish were filled with water to model fluid flow. Two different funnels and one tundish design were originally modeled. A simple rectangular "shoe box" funnel created less turbulent flow that a funnel with tapered walls. The "shoe box" funnel design was selected for the first casting experiments.

Before casting titanium, full-scale models of the new tundish and funnel were fabricated from 6-mm (1/4-in)-thick steel plate. The steel funnel and tundish were mounted onto the melt overflow casting machine. Experiments were performed to cast aluminum Alloy 1100 onto a copper chill roll through the steel funnel and steel tundish to simulate the casting of titanium alloys through a graphite funnel and graphite tundish. The liquid aluminum formed a skull against the steel funnel and tundish. It cast 300-mm (12-in)-wide aluminum strip for approximately 10 seconds before the aluminum in the tundish froze completely. The experiments to cast aluminum strip from a steel

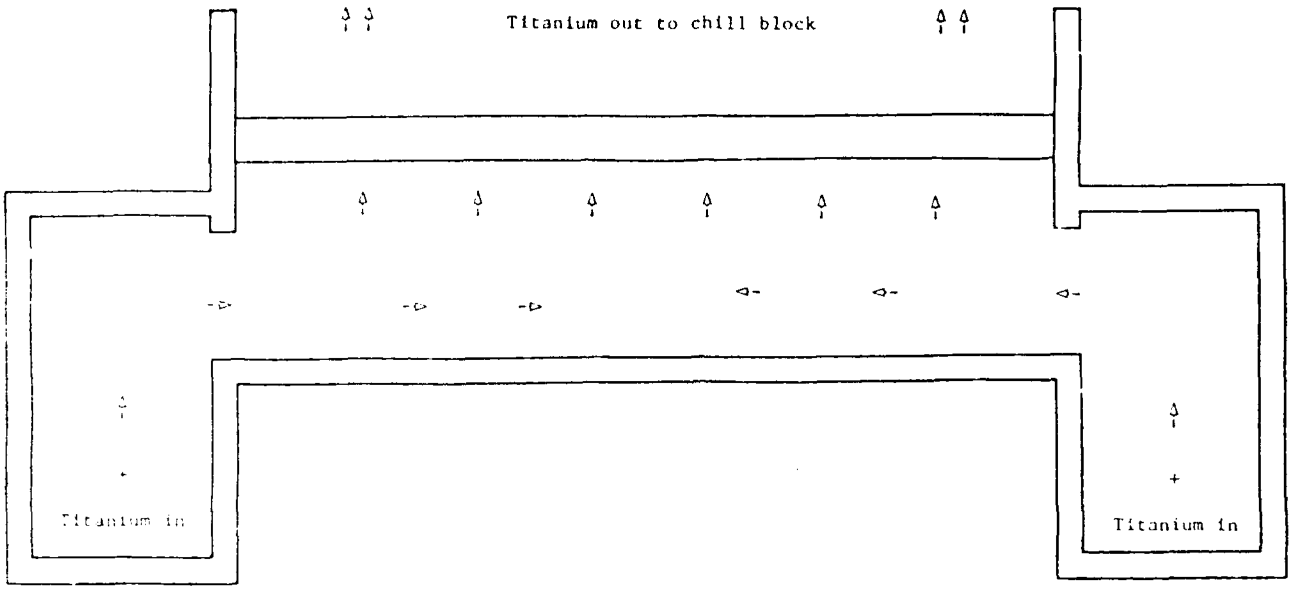


Figure 8: Schematic of the Graphite Tundish (top view)

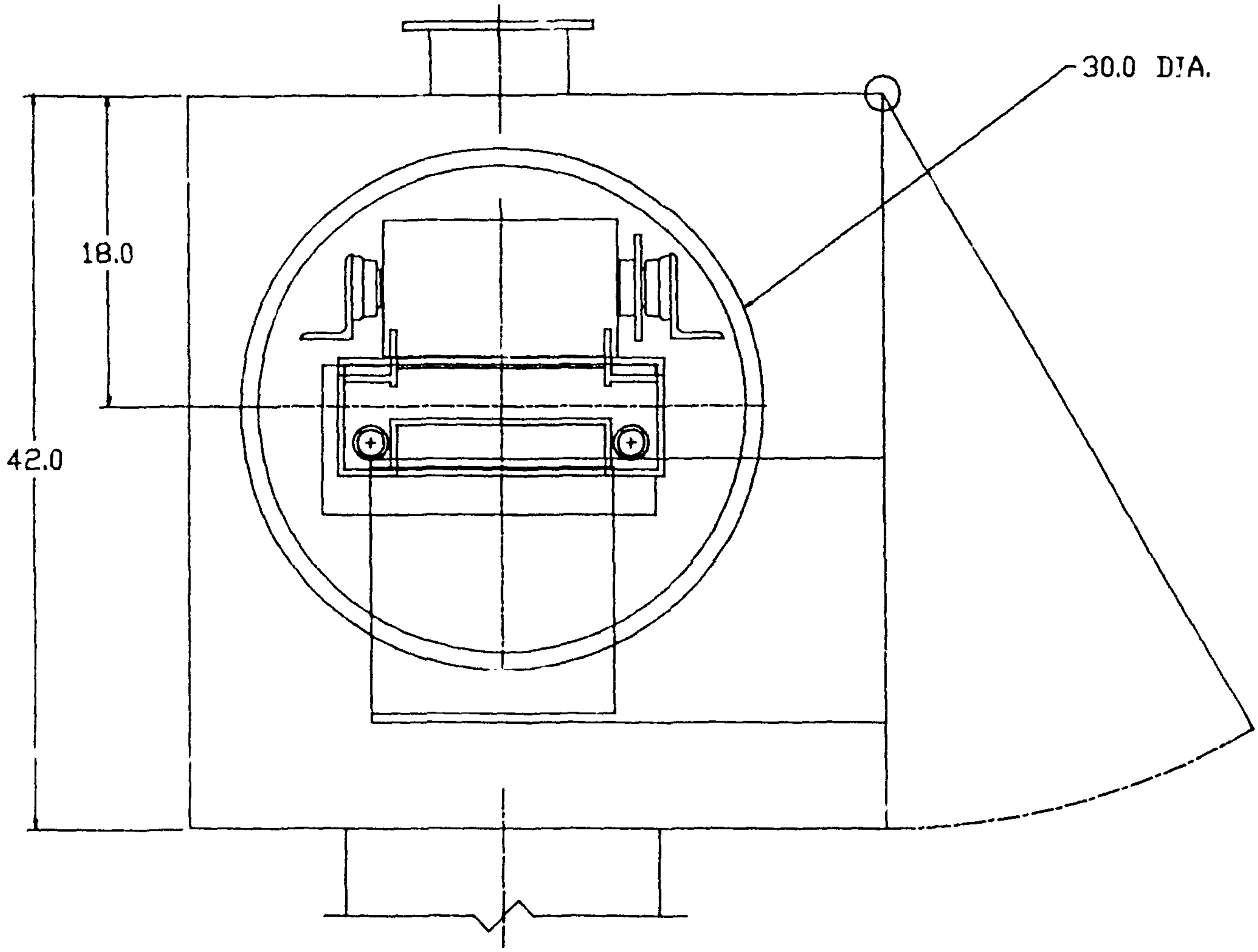


Figure 9: Drawing of Melt Overflow Casting Machine (top view)

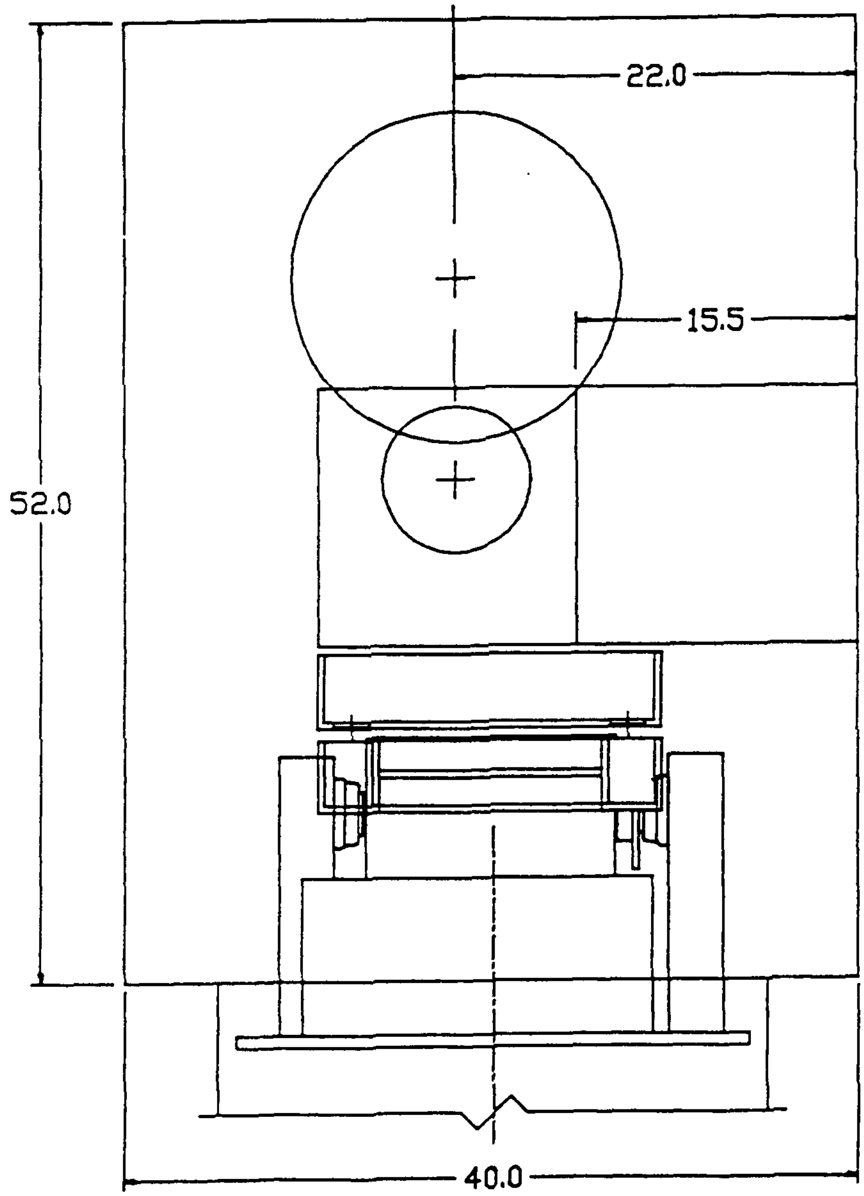


Figure 10: Drawing of Melt Overflow Machine (front view)

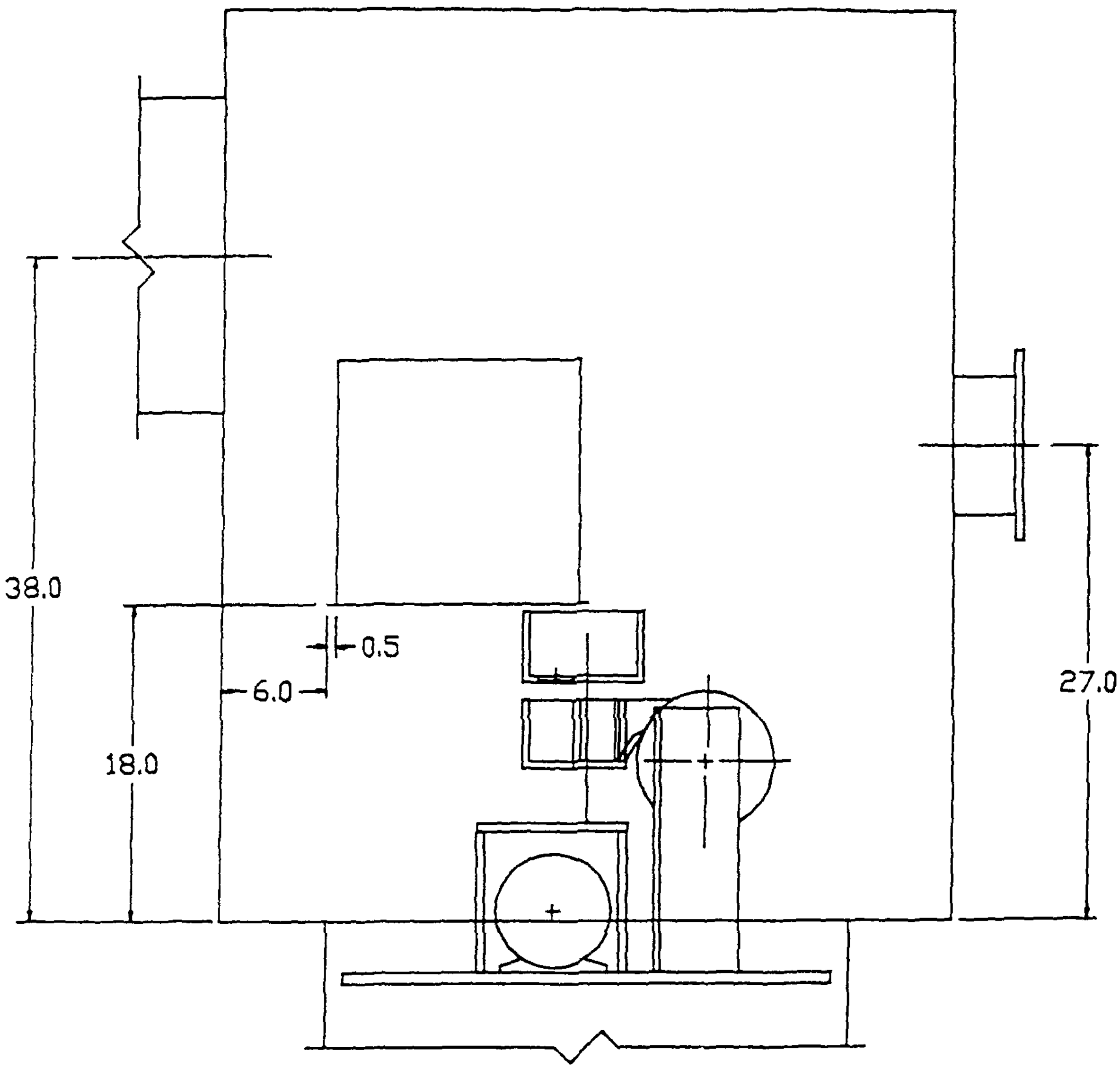


Figure 11: Drawing of Melt Overflow Casting Machine (side view)

funnel and tundish demonstrated that the new tundish andfunnel designs were capable of casting 300-mm (12-in)-wide strip.

During the first two experiments to cast Ti-6Al-4V alloy into strip using the induction skull furnace at Duriron, the splash from the funnel appeared to be excessive. We again used a full-scale acrylic funnel and tundish to model the pouring of titanium with water. These experiments led to modifications of the funnel and tundish designs that were used successfully during subsequent titanium strip casting experiments.

Task IV - Processing Experiments. Twenty-four experiments were performed to cast 300-mm (12-in)-wide titanium alloy strip using induction skull melting with the melt overflow process. Eight experiments were conducted to cast each of three alloys: Ti-6Al-4V, Ti-14Al-21Nb and Ti-34Al-4V. The dimensions of the cast strip are presented in Table 4. The weights of the melting charge, skulls, and cast strip are presented in Table 5. A graphite funnel with two 25-mm (1-in)-diameter orifices was used with a graphite tundish for all experiments.

During Experiment 1, a rectangular "shoe box" funnel was used to direct titanium into the tundish. The tundish had a lip 57 mm (2.25 in) high. In other words, the tundish had to be filled to a depth of 57 mm (2.25 in) before liquid titanium could overflow onto the chill roll. The liquid titanium filled the bottom of the tundish and solidified but did not overflow onto the molybdenum chill roll.

During Experiment 2, the tundish was filled slightly above the "lip" and overflowed to cast a few grams of Ti-6Al-4V alloy strip 50 mm (2 in) wide at a rate of 3 m/s (10 ft/s) on a knurled molybdenum chill roll. In practice, the time required to fill the tundish to a depth of 57 mm (2.25 in) was too great; the liquid titanium froze in the tundish before overflowing to cast strip.

After the first two experiments, the fluid flow in the funnel and the tundish was modeled with water flowing through an acrylic funnel and acrylic tundish. The funnel and tundish were redesigned to hold lower volumes of metal. The tundish was redesigned for a lip height of 6.25 mm (0.25 in). Two different tundish positions were used; the first had the lip on the horizontal center of the chill roll and the second raised the position of the lip to 22° (25 mm) above the horizontal center of the chill roll.

Experiment 3 used the redesigned tundish and funnels. The tundish was positioned 22° above the center of the knurled molybdenum chill roll. These modifications resulted casting of 300-mm (12-in)-wide Ti-6Al-4V alloy strip at a rate of 3.4 m/s (11 ft/s). The strip did not release spontaneously from the

TABLE 4. DIMENSIONS OF DIRECT CAST TITANIUM STRIP

Exp. #	Alloy	Substrate Material	Casting Speed (m/s)	Mean Thickness (mm)	(in)	Maximum Width (mm)	(in)	Strip Weight (kg)
1	Ti-6Al-4V	Mo	3.0	0	0	0	0	0
2	Ti-6Al-4V	Mo	3.0	0.4	0.015	50	2.0	0.06
3	Ti-6Al-4V	Mo	3.4	1.00	0.040	300	12.0	8.20
4	Ti-6Al-4V	Mo	0	0	0	0	0	0
5	Ti-6Al-4V	Mo	5.0	0.30	0.013	150	6.0	3.60
6	Ti-6Al-4V	Mo	3.7	0.3	0.01	200	8.0	4.00
7	Ti-14Al-21Nb	Mo	2.8	0.61	0.024	300	12.0	7.00
8	Ti-14Al-21Nb	Mo	5.5	0	0	0	0	0
9	Ti-14Al-21Nb	Mo	3.8	0.54	0.021	150	6.0	5.80
10	Ti-14Al-21Nb	Mo	5.0	0.78	0.031	215	8.5	0.70
11	Ti-14Al-21Nb	Mo	3.2	0.51	0.020	200	8.0	1.10
12	Ti-14Al-21Nb	Mo	3.0	0.33	0.013	292	11.5	5.75
13	Ti-34Al-4V	Ti	3.0	0.41	0.016	254	10.0	1.85
14	Ti-34Al-4V	Mo	3.0	0.41	0.016	254	10.0	1.27
15	Ti-34Al-4V	Ti	3.0	0.64	0.025	287	11.3	4.35
16	Ti-34Al-4V	Mo	4.0	0.51	0.020	254	10.0	7.30
17	Ti-34Al-4V	Ti	2.0	0.99	0.039	292	11.0	7.85
18	Ti-34Al-4V	Mo	2.0	0.53	0.021	279	11.0	7.76
19	Ti-6Al-4V	Mo	1.5	0.56	0.022	300	12.0	8.80
20	Ti-6Al-4V	Mo	2.5	0.94	0.037	279	11.0	0.80
21	Ti-34Al-4V	Ti	2.0	0.63	0.025	300	12.0	4.80
22	Ti-34Al-4V	Ti	2.0	0.40	0.016	152	6.0	0.20
23	Ti-14Al-21Nb	Mo	2.6	0.45	0.018	298	12.0	8.00
24	Ti-14Al-21Nb	Mo	2.5	0.55	0.022	51	4.0	1.80

TABLE 5. WEIGHTS OF CHARGE, SKULLS & CAST STRIP (kg)

Heat Number	Charge	Funnel	Tundish	Strip	Losses (%)
1	15.9	3.400	6.900	0	35
2	18.2	3.400	11.000	0.064	21
3	18.2	3.200	4.100	8.200	15
4	15.9	3.300	10.300	0	14
5*	15.9	3.900	2.300	3.600	38
6	13.6	3.500	3.900	4.000	16
7	15.9	3.600	3.900	7.000	9
8*	15.9	4.000	2.200	0	N/A
9	15.9	3.500	3.600	5.800	19
10	15.9	3.700	8.700	0.700	18
11*	15.9	3.500	4.300	1.100	44
12	15.9	3.075	2.985	5.750	26
13	17.4	1.820	1.810	1.850	75
14	15.9	2.460	2.620	1.265	60
15	15.9	3.170	6.465	4.350	12
16	15.9	3.720	2.950	7.300	12
17	15.9	3.400	3.370	7.850	8
18	15.9	3.400	2.730	7.760	13
19	15.9	3.170	3.230	8.810	4
20	15.9	3.260	9.750	0.820	13
21	15.9	2.660	2.510	4.750	38
22	15.9	2.700	10.000	0.150	19
23	15.9	4.100	4.200	7.950	0
24	15.9	2.400	3.600	1.800	51

* Tundish Cracked

knurled molybdenum chill roll. The first cast strip traveled around the chill roll until it hit the steel tundish holder and stopped causing the strip to break at the meniscus. The next segment of strip was cast underneath it. This resulted in multiple layers of cast strip accumulating against the chill roll.

Experiment 4 used the redesigned funnel and tundish with the tundish mounted 22° above the center of the roll. No titanium strip was cast because the chill roll motor stopped during the pour due to a motor controller malfunction.

The tundish lip was machined off for Experiment 5. The tundish was mounted on the horizontal center of the knurled molybdenum chill roll. During casting, the tundish broke near the chill roll causing liquid titanium to run out of the tundish. The runout resulted in high losses (Table 5) and cut short the casting time. The widest Ti-6Al-4V alloy strip that was cast measured 150 mm (6 in) and was cast at a rate of 5 m/s (16 ft/s).

The height of the lip was increased to 13 mm (0.5 in) during Experiment 6. The tundish was mounted on the horizontal center of the knurled molybdenum chill roll. Two parallel Ti-6Al-4V alloy strips were cast at a rate of 3.7 m/s (12 ft/s).

The results of the first six experiments to cast Ti-6Al-4V alloy strip indicated that the graphite tundish with a 6-mm (1/4-in)-high lip mounted 22° above the center of the chill roll was the most successful configuration for casting Ti-6Al-4V alloy strip on a molybdenum chill roll. We decided to stop modifying the tundish and funnel and to use the same configuration of the caster as Experiment 3. The following experiments to cast 300-mm (12-in)-wide Ti-aluminide strip all used this same configuration.

Experiment 7 was the first attempt to cast Ti-14Al-21Nb alloy strip with the redesigned melt overflow system. Seven kilograms of 300-mm (12-in)-wide strip was cast on a knurled molybdenum chill roll at a speed of 2.8 m/s (9 ft/s). The strip accumulated in layers against the chill roll. The configuration of the caster and results of the experiment were nearly identical to Experiment 3.

The graphite tundish cracked during Experiment 8 which allowed the liquid titanium to run out of the bottom of the tundish. The knurled molybdenum chill roll was coated with a thick layer of Ti-aluminide. The casting speed was set at 5.5 m/s (18 ft/s) - nearly twice as fast as the previous experiment. It is not known whether strip was cast and adhered to the chill roll, causing the tundish to break, or if the tundish broke from the thermal shock of the liquid titanium being poured into it.

Two separate Ti-14Al-21Nb alloy strips were cast

simultaneously during Experiment 9. The wider strip measured 150 mm (6 in) wide and the narrower strip measured 63 mm (2.5 in) wide. The two strips were separated by a gap of approximately 75 mm (3 in). It is possible that the 3.8-m/s (12-ft/s) casting speed was too high to cast full width strip.

Increasing the casting speed to 5 m/s (16 ft/s) during Experiment 10 resulted in a single piece of strip that measured 215 mm (8.5 in) wide by 300 mm (12 in) long and 0.78 mm (0.030 in) thick. This was the thickest alpha-2 strip cast although the casting speed was 5 m/s (16 ft/s). The controller for the casting machine motor malfunctioned and the casting speed was uncontrolled.

Experiment 11 produced 200-mm (8-in)-wide strip at a rate of 3.2 m/s (10 ft/s). During the casting, the graphite tundish broke causing the knurled molybdenum chill roll to be coated with alpha-2 alloy. It is possible that wider strip could have been cast if the tundish did not break.

Experiment 12 successfully cast 300-mm (12-in)-wide Ti-14Al-21Nb alloy strip on a knurled molybdenum chill roll at a speed of 3 m/s (10 ft/s). The strip collected in layers against the inside of the furnace. It appears that a casting speed of 3 m/s (10 ft/s) was optimal for casting alpha-2 strip on a knurled molybdenum chill roll.

The as-cast Ti-14Al-21Nb alloy strip was thicker than the as-cast Ti-6Al-4V alloy strip, all other factors being equal. The widest alpha-2 strip was cast at speeds in the range of 2.5 m/s (8 ft/s) to 3.5 m/s (11 ft/s) while the narrowest strip was cast at speeds up to 5.5 m/s (18 ft/s).

Experiment 13 was our first attempt to cast Ti-34Al-4V alloy strip on a solid Ti-6Al-2Sn-4Zr-2Mo alloy chill roll that was knurled on the circumference. Initially the system cast nearly 2 kg (4 lb) of 250-mm (10-in)-wide gamma aluminide strip at a speed of 3 m/s (10 ft/s), then it began to throw liquid gamma aluminide against the inner walls of the furnace. After the experiment, it was observed that the graphite tundish was not cracked. We also observed a coating of a white powdery substance on the Ti-6242 chill roll surface on which the strip was cast. The coating may have been an oxide that formed upon heating the Ti-6242 chill roll.

Experiment 14 was our first attempt to cast Ti-34Al-4V alloy on a knurled molybdenum chill roll. We observed a large quantity of liquid gamma aluminide that splashed out of the graphite funnel during the pour. A continuous, 250-mm (10-in)-wide gamma aluminide strip was cast at a speed of 3 m/s (10 ft/s).

Experiment 15 repeated the conditions of Experiment 13 with

significantly better results. The strip cast the full 300-mm (12-in) width of the tundish. The strip stayed on the knurled Ti-6242 chill roll until it contacted the tundish. Once again, a white coating appeared on the Ti-6242 chill roll where the strip contacted it.

The casting speed was increased from 3 m/s (10 ft/s) to 4 m/s (13 ft/s) for Experiment 16 to cast Ti-34Al-4V alloy on a knurled molybdenum chill roll. The width of the strip was 250 mm (10 in) which was the same width cast at 3 m/s (10 ft/s) during Experiment 14.

During Experiment 17, casting speed was reduced to 2 m/s (7 ft/s) to cast Ti-34Al-4V alloy on the knurled Ti-6242 chill roll. This resulted in 290-mm (11.4-in)-wide gamma aluminide strip. The strip thickness of 0.039 in (0.99 mm) was significantly higher than any of the other castings, however.

Experiment 18 attempted to cast Ti-34Al-4V alloy strip on a knurled molybdenum chill roll at a rate of 2 m/s (7 ft/s). Strip 279 mm (11 in) wide was cast. The strip was not as uniform as the strip cast on the knurled Ti-6242 chill roll, however.

Experiment 19 cast 300-mm (12-in)-wide Ti-6Al-4V alloy strip on a knurled molybdenum substrate. Losses were minimal at 4% of charge weight and the cast weight was 55% of the initial charge. Experiment 19 was the first of a series, so the chill roll was at room temperature before casting.

Experiment 20 cast 275-mm (11-in)-wide Ti-6Al-4V alloy strip on the knurled molybdenum substrate that was still hot from the previous experiment. The strip adhered to the chill roll surface and wrapped around the roll. Apparently, the wetting characteristics had dramatically changed from Experiment 19. The temperature of the chill roll was measured at 157°C (315°F) 45 minutes after casting.

Experiment 21 used a knurled Ti-6242 chill roll to cast 300-mm (12-in)-wide Ti-34Al-4V alloy strip at a rate of 2 m/s (7 ft/s). It appeared at times that the strip did not uniformly wet the substrate resulting in holes along the lenghth of the cast strip. The high melt losses were from splashing during pouring. The chill roll was at room temperature before casting.

During Experiment 22, the casting of Ti-34Al-4V alloy strip stopped abruptly because a granule of aluminum from the charge got caught in the chain drive of the chill roll caster. The width of the strip was 150 mm (6 in) before the knurled Ti-6242 chill roll stopped rotating. The tundish volume was completely filled by 10 kg (22 lb) of gamma aluminide.

Experiment 23 cast 8 kg of Ti-14Al-21Nb alloy strip on a

knurled molybdenum chill roll. The strip achieved a maximum width of 300 mm (12 in) and averaged 0.45 mm (0.018 in) thick. All of the melt charge was accounted for in the skulls and strip. The chill roll was at room temperature before casting.

The final experiment, Number 24, cast a small quantity of Ti-14Al-21Nb alloy strip on a knurled molybdenum chill roll. After casting for a moment, the strip adhered to the chill roll and wrapped around it. We did not find any evidence of a cracked tundish. We noted that the chill roll was still hot from the previous experiment.

Task V - Process Evaluation. The titanium alloy strip produced during Task I and Task IV were evaluated by chemical analysis, transmission electron microscopy (TEM) and wavelength dispersive spectroscopy (WDS).

Table 6 shows the results of interstitial elements contained in samples of the as-cast titanium alloy strip. The Ti-6Al-4V samples showed interstitial oxygen levels between 2100 ppm and 2500 ppm. There may have been some contamination from air during Experiment 19 which was reflected by the 2450 ppm oxygen and 275 ppm nitrogen levels.

The interstitial oxygen content of the as-cast Ti-14Al-21Nb strip was significantly lower than the oxygen content of the Ti-6Al-4V alloy strip. The oxygen levels can be generally maintained below 1250 ppm for cast alpha-2 aluminide. Hydrogen levels were elevated during Experiments 10, 11 and 12. The hydrogen content might have been reduced if the graphite parts were furnace dried before casting. The strip cast during Experiment 23, however, showed unacceptably high levels of carbon (500 ppm) and oxygen (4790 ppm). It is unlikely that the strip was contaminated from atmospheric oxygen because the nitrogen level would have been higher than 155 ppm. It is more likely that a piece of alumina insulation fell into the pouring funnel. The insulation contains an organic binder, which could be the source of the carbon contamination.

The levels of interstitial elements in the Ti-34Al-4V alloy were quite low. All of the gamma aluminide samples had oxygen contents below 0.1% with acceptable levels of carbon, hydrogen and nitrogen.

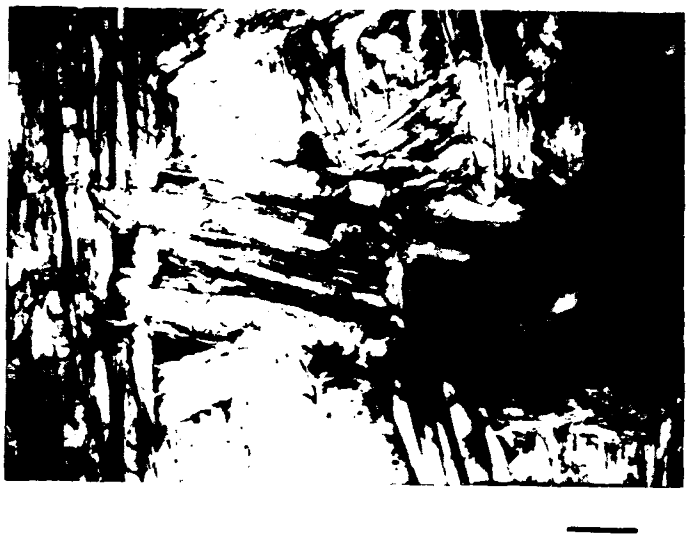
Six samples of as-cast titanium alloy strip were evaluated at the Central Electron Optics Facility at the Ohio State University. Samples of Ti-6Al-4V alloy strip from experiments 3 and 19 were compared. Figure 12 shows a sample of 300-mm (12-in) -wide Ti-6Al-4V strip from Experiment 3. The chill cast surface on the right is considerably smoother than the free cast surface on the left. The thickness of the strip cast in experiment 19 was half the thickness of the strip cast in experiment 3. Both

TABLE 6. CHEMICAL IMPURITIES IN CAST STRIP

Heat Number	C (ppm)	H (ppm)	O (ppm)	N (ppm)	Alloy
3	380	91	2122	124	Ti-6Al-4V
6	230	69	2123	118	Ti-6Al-4V
7-1	260	53	779	97	Ti-14Al-21Nb
7-2	320	51	910	101	Ti-14Al-21Nb
9	210	43	800	115	Ti-14Al-21Nb
10	240	108	1070	113	Ti-14Al-21Nb
11	270	97	960	97	Ti-14Al-21Nb
12	250	88	1223	230	Ti-14Al-21Nb
13	130	20	678	108	Ti-34Al-4V
14	240	40	622	118	Ti-34Al-4V
15	240	26	731	75	Ti-34Al-4V
16	350	24	768	103	Ti-34Al-4V
17	380	22	667	64	Ti-34Al-4V
18	250	24	804	75	Ti-34Al-4V
19	270	66	2450	275	Ti-6Al-4V
21	170	101	950	123	Ti-34Al-4V
23	500	64	4790	155	Ti-14Al-21Nb

Figure 12: Photograph of 300 mm Wide Ti-6Al-4V Alloy Strip

Figure 13: TEM Micrograph of as-Cast Ti-6Al-4V Alloy Strip from Experiment 3 (Magnification: 5000 X)



2μm

Figure 14: TEM Micrograph of as-Cast Ti-6Al-4V Alloy Strip fro' Experiment 19 (Magnification: 5000 X)

specimens exhibited colonies of single-phase martensitic alpha prime laths, shown in Figures 13 and 14. The laths were much coarser in the thicker strip from Experiment 3 (Figure 13) than the laths found in the thinner strip (Figure 14). Distinct habit planes can be distinguished in Figure 14 because of the finer microstructure.

A sample of 215-mm (8.5-in)-wide Ti-14Al-21Nb alloy strip cast during experiment 10 is shown in Figure 15. The sample was cracked during handling after it was cast. This indicates that coiling of cast alpha two strip will be difficult to perform without introducing defects in the strip. The microstructure of this 0.78-mm (0.031-in)-thick sample is shown in Figure 16, and it was compared to the microstructure of 0.33-mm (0.013-in)-thick sample during experiment 12, shown in Figure 17. The microstructures of both samples were dominated by Widmanstattan (acicular) alpha two. There were small pockets of retained beta in both samples. The relatively small fraction of beta may be an indication that the sample was slowly cooled from the beta transus (1135°C). The scale of the microstructures were the same despite the difference in thickness of the two samples. Therefore, we concluded that the solid-state cooling rates were of the same magnitude for the two samples.

The final comparison was made between samples of Ti-34Al-4V alloy strip cast during experiments 14 and 17. The strip from experiment 17 was cast on a Ti-6242 chill roll, and the strip from experiment 14 was cast on a molybdenum chill roll. Also, sample 17 was more than twice as thick as sample 13. A photgraph of a sample of strip from Experiment 17 is shown in Figure 18. There were fewer cracks in the gamma aluminide strip than the alpha two strip. The microstructure of gamma aluminide strip cast during Experiment 14 (Figure 19) was dominated by regions of equiaxed gamma. There were also colonies of thick lamellar gamma with thin, inter-lamellar alpha-2. By comparison, the microstructure of the strip from experiment 17 (Figure 20) was dominated by the lamellar gamma with inter-lamellar alpha-2. The laths were inclined which give them the appearance of being wider. Actually, the scale of the two lamellar structures were similar.

The composition of the gamma aluminide strip cast on a Ti-6242 chill roll during Task I was measured using wavelength dispersive spectrometry (WDS) at the Air Force Materials Laboratory. The alloy specification was 48 a/o Al, 3 a/o V balance Ti. The WDS results presented in Table 7 confirm that the strip was cast within compositional limits.

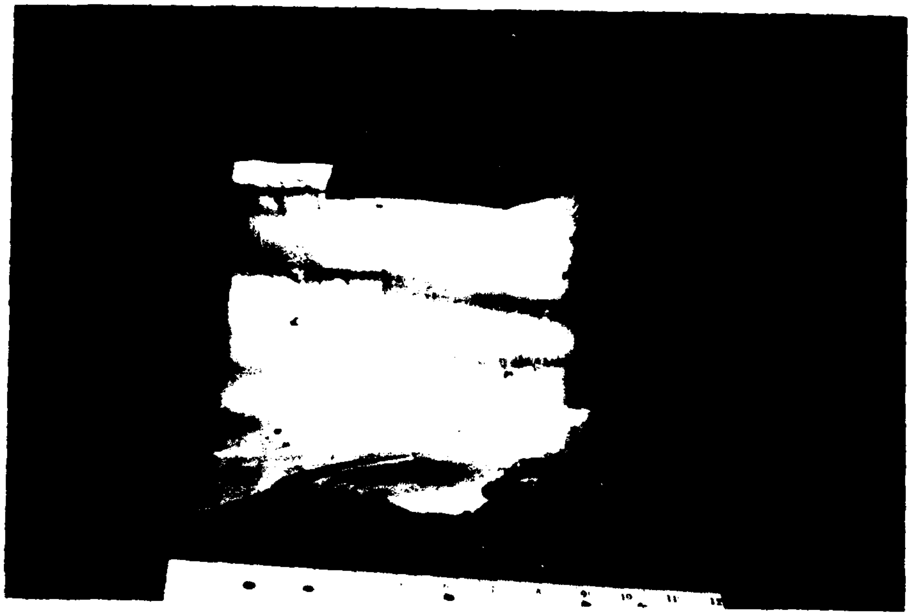


Figure 15: Photograph of 215 mm Wide Ti-14Al-21Nb Alloy Strip

Figure 16: TEM Micrograph of as-Cast Ti-14Al-21Nb Alloy Strip from Experiment 10 (Magnification: 5000 X)

Figure 17: TEM Micrograph of as-Cast Ti-14Al-21Nb Alloy Strip from Experiment 12 (Magnification: 5000 X)

Figure 18: Photograph of 292 mm Wide Ti-34Al-4V Alloy Strip

Figure 19: TEM Micrograph of as-Cast Ti-34Al-4V Alloy Strip from Experiment 14 (Magnification: 5000 X)

$2 \mu m$

Figure 20: TEM Micrograph of as-Cast Ti-34Al-4V Alloy Strip from Experiment 17 (Magnification: 5000 X)

TABLE 7. COMPOSITION Ti-34Al-4V ALLOY STRIP

	Al (at %)	Ti (at %)	V (at %)
A-1	47.85	49.15	3.00
A-2	47.06	49.84	3.10
A-3	46.56	50.43	3.01
A-4	49.24	47.68	3.09
B-1	44.39	52.51	3.10
B-2	49.03	48.07	2.90
B-3	45.35	51.17	3.48
B-4	45.58	51.30	3.12
C-1	48.24	48.73	3.03
C-2	48.22	48.87	2.91
C-3	45.01	51.78	3.21
C-4	47.15	49.86	2.98
Mean	46.97	49.95	3.08
S.D. (n-1)	1.61	1.52	0.16

DISCUSSION

This research project successfully demonstrated the feasibility of induction melting titanium aluminide alloys in a segmented copper crucible and casting them into solid strip up to 300 mm (12 in) wide from a graphite tundish using melt overflow rapid solidification technology (MORST). All three alloys were cast into 300-mm (12-in)-wide strip, shown in Table 6. The data in Tables 2 and 3 show that the objective of casting 0.125 mm (0.005 in) thick titanium aluminide strip can also be realized. This objective was accomplished during experiments 4, 7, 10, 14 and 21 in Table 2 and experiments 8 and 21 in Table 3. However, we did not cast strip that was both 300-mm (12-in)-wide and 0.125-mm (0.005-in)-thick.

The process parameters having the greatest influence on the thickness of the cast strip were the casting speed, the depth of liquid in contact with the substrate, and the physical properties of the liquid (viscosity and surface tension). Factors that influence the melt depth were the pouring volume and rate of the induction skull furnace, the orifice diameters in the funnel and the fluidity (superheat) of the liquid. The furnace pour rate was constant during each experiment, but the volume of liquid being poured can vary depending on the amount of remelt stock that was charged in the segmented copper crucible. The superheat varies from alloy to alloy and depends on several factors, which include the liquidus temperature, the electrical conductivity and the thermal conductivity of the alloy.

The melt overflow system used for these experiments did not achieve steady-state casting conditions. In fact, the casting conditions were continually changing: as the liquid drained from the funnel to the tundish, the mass flow rate of liquid decreased with time. The level of liquid in the tundish continually changed because the flow from the funnel decreases with time and the solid skull that forms inside the tundish increases with time.

It appears that the wetting characteristics of liquid titanium alloys on metallic substrates were greatly affected by the substrate temperature. The most successful series of experiments were performed on September 21, 1989, when we alternated use of a molybdenum and Ti-6242 chill roll. This allowed time for one chill roll to cool while the second chill roll was casting strip. If the same chill roll was used for consecutive experiments, the titanium did not cast as well on a hot substrate. Clearly, more research is needed to find the optimal substrate temperature for casting titanium alloys.

Collection and handling of the as-cast strip will be essential for recovering any useful lengths of material. We attempted to direct the strip off the chill roll with a sheet-

metal guide, but it was not effective. The processing experiments (Task IV) were complicated by position of the melt overflow casting machine in the Duriron furnace: there was not enough room to collect the strip after it was cast.

The low ductility of the cast alpha-2 and gamma aluminide strip will further complicate handling and coiling of the strip after it is cast. Experiments performed at Ribtec to cast Ti-aluminide strip with the plasma melt overflow furnace show that the titanium aluminide ribbons were extremely brittle in the solid state and break up after casting. The Ti-aluminide strip may require heating during coiling to improve ductility. It is anticipated that collection of the strip will be addressed in a Phase III research project.

The uniformity of thickness of the as-cast strip was poor. Generally, one standard deviation in thickness represented 15% of the mean thicknesses reported in Table 4. In addition, the free cast surfaces often exhibited a rough, pebbled appearance. Clearly, secondary processing of the direct cast strip will be required, at this stage of development. It is likely that grinding of the as-cast strip, followed by rolling, is feasible to produce the optimum physical and mechanical properties.

CONCLUSIONS

- Direct casting of titanium alloy strip up to 300 mm (12 in) wide is feasible by combining induction melting of titanium alloys in a segmented crucible with melt overflow rapid solidification technology.

- Direct casting of titanium alloy strip as thin as 0.125 mm (0.005 in) is feasible by melt overflow rapid solidification technology.

- The combination of induction melting of titanium alloys in a segmented copper crucible with melt overflow rapid solidification technology casts strip that has low levels of oxygen, hydrogen, nitrogen and carbon. There was no evidence of carbon contamination from the graphite tundish.

- A new graphite tundish system was invented for overflowing the liquid titanium onto the chill roll. This invention made casting of 300 mm wide titanium strip possible. A U.S. patent application was filed on the invention.

- The substrate temperature affects the wetting of titanium alloys on the substrate. If the substrate temperature was too high, the liquid titanium will not wet a solid chill roll.

- Proper handling of the strip after solidification will be essential if continuous lengths of titanium strip are to be produced. Ti-aluminides may require additional heating during coiling operations to increase ductility.

- The microstructure of the Ti-6Al-4V alloy exhibited colonies of single-phase martensitic alpha-prime laths. Thicker cast strip resulted in coarser laths.

- The microstructures of the Ti-14Al-21Nb samples were dominated by Widmanstatten (acicular) alpha two. There were small pockets of retained beta in the samples which indicated a fairly slow cooling rate in the solid state.

- The microstructures of as-cast gamma aluminide strip contained regions of equiaxed gamma and colonies of thick lamellar gamma with thin, inter-lamellar alpha-2. The microstructure of the 1-mm (0.039-in) thick gamma strip was dominated by the lamellar gamma with inter-lamellar alpha-2 while the microstructure of 0.4-mm (0.016-in)-thick gamma strip was dominated by equiaxed gamma.

RECOMMENDATIONS

- Build an induction skull furnace dedicated to casting titanium strip. The furnace should be large enough to contain the casting machine and coiling equipment. A bottom pour segmented crucible might eliminate the need for a graphite funnel.

- Use a pyrometer to measure the temperature of the liquid titanium in the induction skull furnace and in the funnel and tundish.

- Use water cooling to control the temperature of the chill roll during casting of titanium strip. The surface temperature of the chill roll could be measured with an infrared thermal imaging system to map the temperature of the substrate surface and the solidifying strip.

- Design a system for coiling the strip as it is cast to reduce or eliminate defects on the strip. A belt wrapper might be used with a secondary heating system to coil the strip at temperatures above the beta transus.

- Evaluate techniques like secondary chill rolls, continuous belts, or forced gas convection knives for directing the strip into the coiling equipment and study the thermal effects on the solid strip.

- Investigate grinding, hot rolling and cold rolling of the as-cast strip to achieve final ribbon dimensions and physical properties.

- Investigate the feasibility of casting titanium alloy strip at least 600 mm (24 in) wide.

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